Investigation of contaminated plumes caused by pyrite oxidation from a coal refuse pile at the Alborz Sharghi coal washing plant using VLF geophysical method

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Abstract A very low frequency electromagnetic (VLF-EM) method was applied to detect contamination plumes caused by the tailings impoundment and coal refuse piles of the Alborz Sharghi coal washing plant, Shahrood, northeast Iran. Fraser filtered and Karous-Hjelt filtered maps identified conductive bodies related to the tailings impoundment located in the northwest and refuse piles that covered the northern part of the profiles. Two-dimensional (2D) resistivity models by inversion of the tipper data indicated a contaminated zone with a resistivity lower than 25 Ω m at the different depths in the downstream of the coal refuse piles.

Key Words Environmental pollution, acid mine drainage (AMD), Alborz Sharghi, VLF-EM method, Inverse modeling

Introduction

Coal washing refuse materials may contain high content of pyrite. Acid mine drainage (AMD) is often produced while pyrite is exposed to the atmosphere (Atkins and Pooley 1982). It has been recognised to be the major source of the environmental problems. Therefore, AMD not only occurs due to mining operations, it may take place in sites where refuse materials consisting of pyrite.

According to Eqs. 1 to 3, AMD is characterised by high concentrations of Fe^{2+}, high sulphate and low pH (Singer and Stumm 1970; Williams *et al.* 1979; Doulati *et al.* 2004).

$$FeS_2+7/2O_2+ H_2O \rightarrow Fe^{2+} +2SO_4^{2-}+2H^+ \qquad (1)$$

$$Fe^{2+} +1/4O_2+ H^+ \rightarrow Fe^{3+} +1/2\ H_2O \qquad (2)$$

$$FeS_2+14Fe^{3+}+ 8H_2O \rightarrow 15Fe^{3+} +2SO_4^{2-}+16H^+ \qquad (3)$$

Previous investigations carried out by Doulati Ardejani *et al.* (2011) revealed that the pyrite oxidation Process within the refuse materials in the Alborz Sharghi caused leaching of metals. The concentrations of metals increased with depth of pile materials. The elevated concentrations of trace elements including Fe, Mn, Zn, Cr and Co were found at depth 2 m. Pyrite oxidation at the upper 75 cm of the refuse pile has resulted in a pick concentration of SO_4 (349 m.e/L at depth 0.5 m) and low pH (pH=3.7; Doulati Ardejani *et al.* 2008 a).

Since AMD generation and leaching of the oxidation products may increase the concentration of dissolved metals in the groundwater aquifer. This can change the electrical conductivity of the medium. Hence, the geophysical methods such as electrical and electromagnetic methods could be effectively used to detect the polluted zones. Fig. 1 shows a general view of the Alborz Sharghi coal washing plant. The coal refuse piles are also illustrated.

Different geophysical methods have been utilised to investigate the environmental problems related to the human activities. VLF-EM technique is one of the famous electromagnetic methods for detection of the distribution of conductivity of the subsurface structures. Especially this method is useful for exploration of the fracture zones associated with groundwater and relevant contamination (ABEM 2000; Sharma and Baranwal 2005; Monteiro Santos *et al.* 2006; Al-Tarazi *et al.* 2008). In this method, transmitter stations in all over the world produce radio signals with frequency range between 10—30 kHz. These signals are used to detect anomalous bodies with the VLF-EM receiver instrument (McNeill and Labson 1991; Telford *et al.* 1998). In the VLF-EM method, the components of the elliptically polarised magnetic field are measured, while if both horizontal electric and magnetic fields are measured, this method is named the VLF-R method (Oskooi and Pedersen 2005).

The main aim of this study was to map the leachate plumes associated with the tailings impoundment and the coal refuse piles in the Alborz Sharghi coal washing plant (figs. 1 and 2) with the VLF-EM method. Distribution of the contamination plumes in subsurface at the downstream of the tailings impoundments and the coal refuse piles may cause aquifer contamination

The study area is a part of the Tazareh coal region. From geological point of view, the area consists of sandstone, thin bedded coaly shale of the Shemshak formation, new alluvial deposits and old alluvial fan with gravel marl and quartz. Coal in the region is mined by the Alborz Sharghi coal company. Although not shown, the VLF-EM profiles are located in the area that covered by alluvial fan.

Alborz Sharghi coal washing plant has being worked for 32 years. Separation of the coal from the refuse materials is a necessary part of the

Figure 1 *View of the Alborz Sharghi coal washing plant, coal refuse piles and tailing impoundment.*

process that is done in this plant. So, the coal extracted from the Tazareh, the Gheshlagh and the Tabas coal deposits are washed in this plant. The processed coal is then being transported to the Isfahan and is used for steel industry. As Fig. 1 shows, large piles of refuse materials have been left. They generally are responsible for environmental degradation including acid mine drainage generation as well as being hazards (Doulati Ardejani *et al.* 2011).

The input unwashed coal to the plant is 600, 000 ton per year. The coal recovery in the plant is 50 percent. After dewatering process of the rest of the coal in tailings impoundment, they are transported by trucks and dumped as waste materials at the immediate distance from the plant. Depending on the method is being used for coal washing,

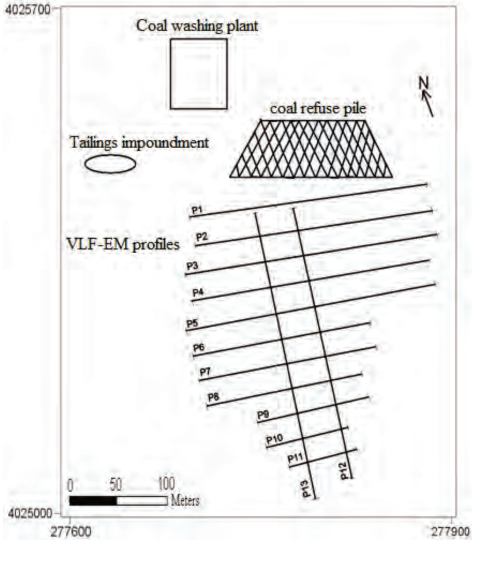

Figure 2 *Location map of the Alborz Sharghi coal washing plant, coal refuse pile, tailings impoundment and thirteen VLF-EM profiles.*

two kinds of the waste are produced and dumped in distinct places. These are the waste produced by jig machine and that produced by flotation process. It has been expected that the amount of the coal waste in the study area to be about 3 million tons (Doulati Ardejani *et al.* 2008 b).

The average elevation of the site is 2600 m.; having a moderate topographical condition. The main access road to the study area is Mehmandoust - Tazareh coal mine road. The average annual precipitation at the site is 253 mm. The nearby lands of the area (about 10 km far from the site) are under agricultural activities. The study area can be important for the wild life. The temperature varies from about 40 °C in summer to -15 °C in winter.

Methods

Interpretation of measured data

VLF-EM method was performed using a WADI (ABEM) instrument on 11 parallel profiles at approximate direction of east-west and on 2 profiles at approximate direction of north-south with measuring spacing of 10 m in downstream of coal refuse piles of the Alborz Sharghi coal washing plant (fig. 2). The UMS station with a frequency of 17.1 kHz and the GBZ station with a frequency of 19.6 kHz were selected for east-west and north-south profiles respectively. Fig. 3 shows, for instance, the real and imaginary components of VLF-EM data measured along two profiles p5 and p13. Solid lines represent the response of the model for real component and dashed line stands for the response of the model for imaginary component.

Fraser filter

Fraser filtering is a common method for processing of VLF-EM data. It is a useful tool applied for a qualitative interpretation (Fraser 1969). Based on Eq. 4, the Fraser filter shifts crossover points into peaks. A linear filtering approach is practically

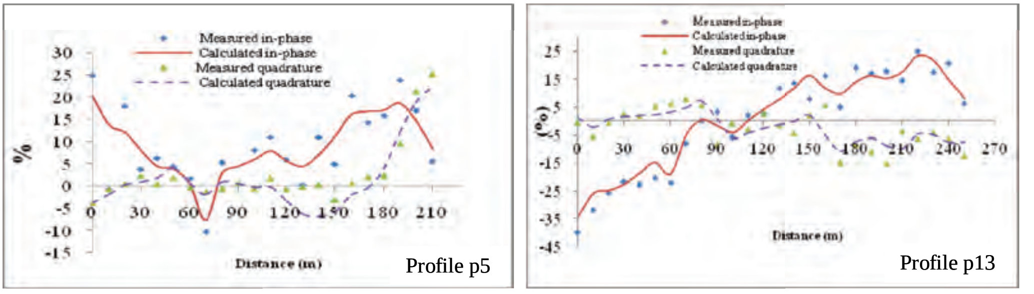

Figure 3 *Real and imaginary components of VLF-EM data measured along profiles p5 and p13. Solid lines represent the response of the model for real component and dashed line represent the response of the model for imaginary component.*

used for in-phase component because this component is sensitive to low resistivity structures (Monteiro Santos *et al.* 2006; Al-Tarazi *et al.* 2008).

$$F_{2,3} = (M_3+M_4) - (M_1+M_2) \quad (4)$$

where, M_1, M_2, M_3 and M_4 are four continuous measurement points, respectively. In fact $F_{2,3}$ belongs to the point between M_2 and M_3. Moreover, $F_{3,4}$ located between M_3 and M_4 (Fraser 1969). Continuously, $F_{i,i+1}$ generated between M_i and M_{i+1}. This filter is effective for quantitative interpretation of conductive bodies. However, a shift may occur in the location of targets sometimes.

Fraser filtered map of the in-phase component (Sundararajan *et al.* 2006; Al-Tarazi *et al.* 2008) is one the qualitative method for a primary interpretation. Fig. 4 shows a fraser filtered map for profiles p1 to p11. Positive continuous anomalies with two sources may be interpreted to the leachates

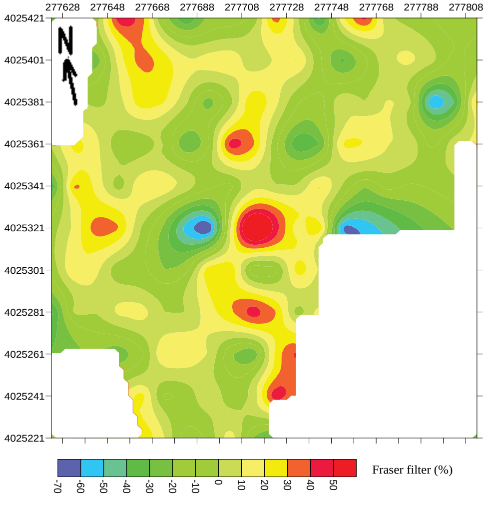

Figure 4 *Fraser filtered map of real component obtained from 11 profiles at the direction of the E-W.*

from the refuse pile with an extension from approximate direction of north and the tailing impoundment located in the northwest of the study area. In the northern part, three sources with positive values are visible. These plumes migrated downstream and jointed together in the central part of map. The migration is further continued to downstream to join a leachate plume emanated from the tailings impoundment in the lowest part of the map.

Karous-Hjelt filter

Karous-Hjelt filtering (Karous and Hjelt 1983) is often implemented to identify the conductive structures. In this paper, KHFFILT computer program (Pirttijarvi 2004) is utilised to represent the current density pseudo-section based on the real component. Fig. 5 shows the current density pseudo-section mapped based on 11 profiles. Profile p1 illustrates different locations with high current density values, especially a narrow section from 65 to 95 m. The east part of the cross-section, from 180 to 215 m, shows the lowest extension depth. A higher value of current density can be seen in the western part of profile p2 between 40 and 125 m. Interpretation for profile p3 is similar to profile p2. However, the intensity of current density is low in the eastern part. Conductive bodies are visible in the beginning and ending of most profiles with a narrow trend to the south corresponding to the length of profiles. It seems that the conductive structures have two sources in these profiles: the first is the coal refuse pile located in the north of the survey location. The second one is the tailing impoundment in the northwest. The study area is covered by alluvial fan. High porosity of these alluvial is a good reason allowing seepage from refuse pile and tailings leachates and their transportation to the downstream. Pyrite oxidation in the refuse pile results leaching of some heavy metals including Fe, Mn, Cr and Co. This increases the conductivity of the materials of groundwater aquifer.

2D inversion model

Primary electromagnetic field travels through the ground and causes eddy currents in conductive bodies. The secondary magnetic field is produced by this induced current. The VLF receiver senses the horizontal (H_Z) and vertical (H_Y) components of magnetic field. $B = H_Z / H_Y$ called a scalar tipper data. Measuring of parameter B in each site yields a quantitative interpretation (McNeill and Labson 1991; Monteiro Santos *et al.* 2006; Al-Tarazi *et al.* 2008; Gürer *et al.* 2009).

The use of single frequency VLF-EM data has been employed by several researchers to perform quantitative interpretations (Chouteau *et al.* 1996; Beamish 2000; Monteiro Santos *et al.* 2006; Al-Tarazi *et al.* 2008). In this paper, INV2DVLF software (Monteiro Santos 2007) was used to interpret VLF-EM data quantitatively. Two resistivity profiles employing Wenner array were performed on profiles p3 and p5 to generate an initial model proportion to 200 Ω m.

Fig. 6 illustrates two-dimensional resistivity models which were obtained by the inversion of VLF-EM data. In profile P1, resistivity decreased to less than 25 Ω m at distance between 205 to 220 m and depths from 8 to 26 m. Similarly, two zones with resistivity lower than 25 Ω m is evident on profile P5: the first anomaly is characterised by a depth of 40m and a center at 25 m. The second one with two small halos inside of zone with resistivity lower than 50 Ω m is obvious at distance between 180 to 200 m and depths between 20 to 40 m. In profile P7, resistivity is less than 25 Ω m at distance between 110 and 140 m and for depths below 20 m. A conductive zone can be seen at distance between 60 and 80 m on profile P8 with an expansion to the left. The centre of this anomaly has an approximate depth of 20 m. Although not shown here, on profile P9, at distance between 130 to 150 m and for depths from 15 to 25 m, the zones with resistivity lower than 50 Ω m represent contamination zones.

Conclusions

The results obtained from the qualitative interpretation of VLF data shows different pathways to transport contaminants. According to the Fraser filter map and Karous-Hjelt pseudosection, two sources of contamination can be possibly recognised: (a) infiltration from tailings impoundment into subsoil and groundwater in the northwest and (b) pyrite oxidation and acid mine drainage generation in the coal refuse pile in north of the study area. Transportation of the oxidation products, in particular, metals through the subsurface is the main cause in resistivity decrease. Two-di-

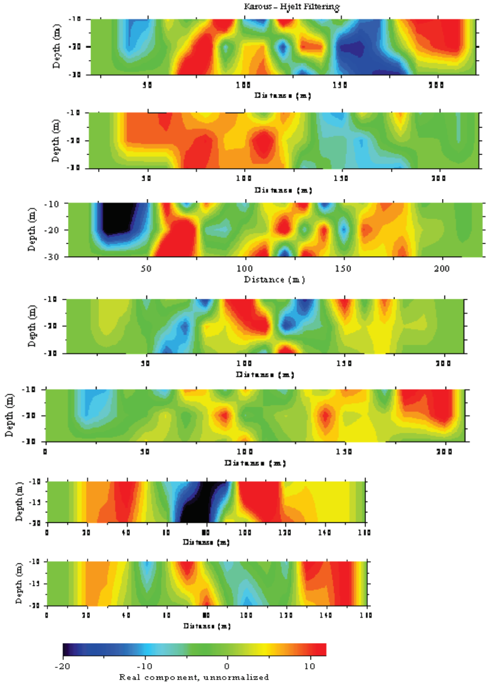

Figure 5 *Current density pseudo-section for real component calculated using Karous-Hjelt filter for profiles p1 to p7.*

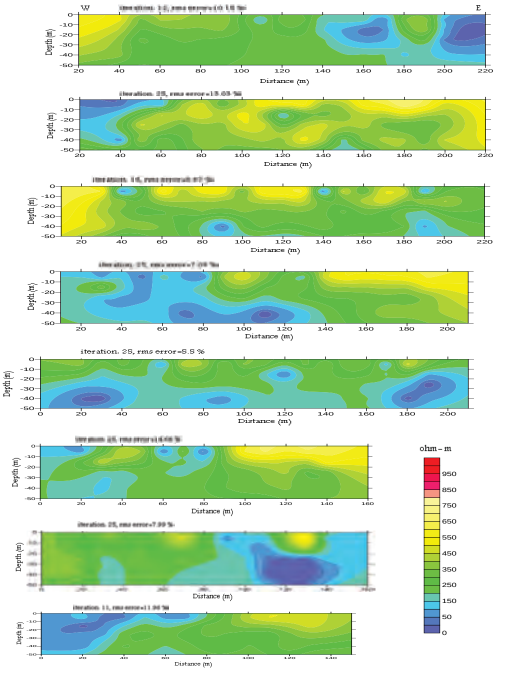

Figure 6 *Two-dimensional resistivity models obtained from the inversion of the VLF-EM data for profiles p1 through p8.*

mensional resistivity models which were obtained from the inversion of the VLF-EM data indicate leachate plumes at different depths with resistivity values lower than 25 Ω m. The zones with the resistivity values between 25 and 50 Ω m may be related to the contamination areas. Although not given here, the previous geochemical and hydrogeochemical analyses of refuse pile materials, soil, surface water and groundwater confirm increasing of trace elements to subsurface due to leaching from the waste pile and show a close agreement with the VLF-EM method.

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